

A SPECTROGRAPHIC STUDY OF ϕ PERSEI

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Reprinted for private circulation from
THE ASTROPHYSICAL JOURNAL, Vol. 84, No. 5, December 1936
PRINTED IN THE U.S.A.

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ABSTRACT

The spectral variations of ϕ Persei were measured on 32 two-prism spectrograms. The radial velocity of the central absorption of hydrogen shows cyclic variations in a period of 126.6 days with a secondary variation on the descending portion of the velocity-curve which increases progressively with decreasing wave-length. Microphotometric studies of the intensities of the hydrogen absorption and of the emission components of hydrogen show similar variations.

At maximum positive velocity of the hydrogen absorption the red edges of the hydrogen emission show a similar displacement to the red, while the violet edges show a violet displacement, resulting in a maximum width for the total emission and in a maximum intensity of the violet emission component relative to the red emission component. At maximum negative velocity of the hydrogen absorption the violet edges of the hydrogen emission show a similar violet displacement, while the red edges show a red displacement, resulting in a second maximum width for the total emission and in a maximum intensity of the red emission component relative to the violet emission component. The widths of the hydrogen emission and the components vary therefore in one-half of the star's velocity period, while the relative intensity of the emission components and of the central absorption of hydrogen relative to the continuous spectrum show periodic and secondary variations similar to the star's velocity of hydrogen absorption.

The truly periodic spectral variation of ϕ Persei is interpreted satisfactorily by the hypothesis of orbital motion and rapid axial rotation of two stars, each having a very extensive atmosphere. The hydrogen emission is assumed to originate in the projecting atmospheres of the stars at right angles to the line of sight. The hydrogen absorption is assumed to originate mainly in the outer atmosphere between the observer and the fairly well-defined bright photosphere of the primary star. The pronounced secondary spectral variations, which vary progressively with wave-length, appear to be explained most readily by an apparent atmospheric expansion which is produced in the intervening extensive, rarefied, and transparent atmosphere of the companion star due to excitation by radiation from the hot photosphere of the primary star at the time it is partially eclipsed by the extensive atmosphere of the companion star.

INTRODUCTION

The spectrum of ϕ Persei, class Bope, is of unusual interest because of the great variations of the hydrogen lines. Each line consists of a very broad absorption upon which is superimposed a narrower emission. The emission is divided into two components by a sharp central absorption. The emission is very strong for $H\beta$ but vanishes rapidly for lines below $H\delta$.

The spectral variations of this star have been extensively investi-

¹ A dissertation submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the University of Michigan (1928). The general results were presented at the annual meeting of the Iowa Academy of Science, April, 1929. In preparing this paper for publication several additions have been made, as well as many excisions.

gated by Campbell and Reese,² Cannon,³ Ludendorff,⁴ Jordan,⁵ Frédette,⁶ Lockyer,⁷ and Dustheimer.⁸ The radial velocity of the central absorption of hydrogen has been found to vary in a period of 126.6 days. The relative intensities of the hydrogen emission components vary in a similar period. The results of Lockyer in 1925 indicate a cyclic variation of intensity in a period of 21 days in addition to the 126-day period. Subsequent data published by him in 1926, however, do not confirm this short period. The widths of the hydrogen emission lines show a cyclic variation in one-half of the star's velocity period. Photoelectric measurements by Guthnick⁹ during 1916-17 indicate a cyclic variation of about 0.11 mag. in a period of 18.1 days. This short period corresponds to that determined from his visual observations in 1911-12. The photoelectric measurements by Güssow¹⁰ during 1925-28 indicate variations of about 0.1 mag. which do not satisfy the previously announced periods.

With the attachment of the two-prism spectrograph to the Ann Arbor 37½-inch reflector in the summer of 1927, it seemed worth while to obtain a series of two-prism spectrograms of φ Persei for a more accurate study of its spectral variations. Thirty-two spectrograms were obtained over an interval slightly more than the star's velocity period. On each two-prism plate ten standard intensity spots were photographed by means of a tube-sensitometer.

The results which will be presented in this paper include a study of the intensity variations of the hydrogen lines with the Moll microphotometer, of the widths of the hydrogen emission lines and components, and of the measures for radial velocity of the following features: the central absorption of $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, and $H\zeta$; the central absorption edges of $H\beta$, $H\gamma$, and $H\delta$; the emission edges of $H\beta$, $H\gamma$, and $H\delta$; K of calcium; helium at $\lambda\lambda$ 3964, 4026, and 4471; and the central absorption of ionized iron at $\lambda\lambda$ 4233, 4352, 4584, 4630,

² *Lick Obs. Bull.*, **1**, No. 20, 158, 1902.

³ *J.R.A.S., Can.*, **4**, 195, 1910.

⁴ *A.N.*, **186**, 17, 1911.

⁶ *J.R.A.S., Can.*, **19**, 185, 1925.

⁵ *Pub. Allegheny Obs.*, **3**, 31, 1913.

⁷ *M.N.*, **85**, 580, 1925; **86**, 474, 1926.

⁸ Dissertation, University of Michigan, 1927, unpublished.

⁹ *Veröff. Kgl. St. Babelsberg*, **2**, 89, 1918.

¹⁰ *A.N.*, **237**, 321, 1929.

and 4924. Some results of the intensity variations of the hydrogen emission, obtained from 109 unstandardized single-prism spectrograms, are presented for comparison.

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Relative intensities.—The variations with phase in the intensity of the hydrogen lines of ϕ Persei are shown in Figure 1. The intensity

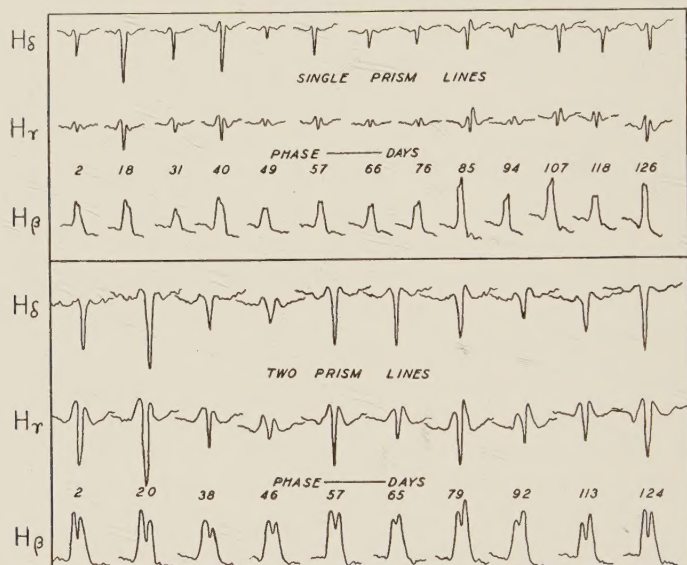


FIG. 1.—Microphotometric tracings showing the periodic variation in the intensity of the hydrogen lines of ϕ Persei.

variations were determined quantitatively with the aid of the standard spots. The results are expressed in an arbitrary unit which is equal to the logarithm to the base 10 of 1.5, that is, the logarithm of the ratio of the aperture areas of the tube-sensitometer.

The relative intensities based upon the individual two-prism plates are given in Figure 2. The period used in computing the phases and the epoch to which they are referred are those given by Dustheimer, namely, a period of 126.626 days and zero phase at November 18.000, 1925, G.M.T.

The curves for the relative intensities of the emission components

of $H\beta$, $H\gamma$, and $H\delta$, at the bottom of Figure 2, show that at zero phase the violet emission component is slightly more intense than the red emission component. This difference in intensity increases with phase and becomes a maximum at approximately 28 days. On the descending portion of the curves, in the region where the intensity of the red emission component is approximately equal to that of the violet emission component, the curves show a secondary varia-

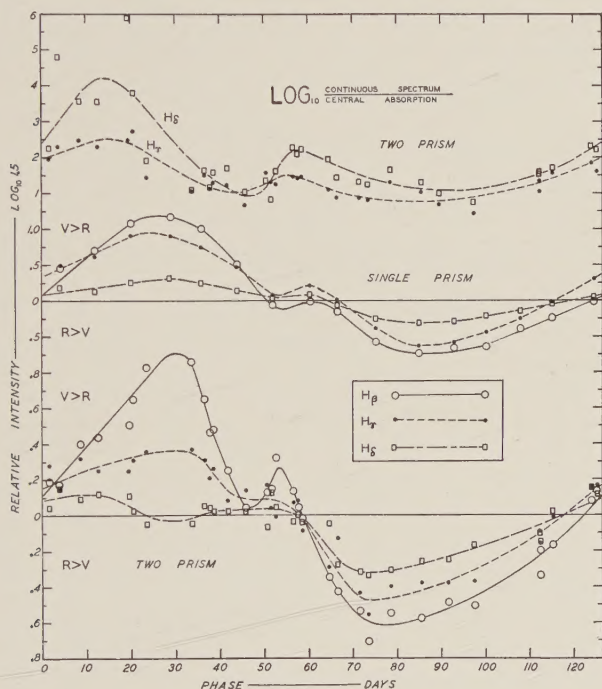


FIG. 2.—Relative intensity of the hydrogen emission components and of the central absorption of hydrogen relative to the continuous spectrum of φ Persei.

tion. Beyond phase 60 days the intensity of the red emission component is greater than that of the violet emission component. The difference is a maximum between phases 70 and 80 days and then decreases again to complete the cycle in 126.6 days.

The range of variation appears to increase with the wave-length. The secondary variation which is pronounced in $H\beta$ is only indicated for $H\gamma$ and is practically absent in $H\delta$. The absence of a dis-

tinct maximum at phase 28 days for $H\delta$ and the shape of the secondary variation for $H\gamma$ suggest that the secondary variation occurs earlier and may be of greater magnitude in lines of shorter wavelength.

TABLE I
RADIAL VELOCITIES OF φ PERSEI IN KM/SEC

DATE (G.M.T.)	PHASE (DAYS)	CENTRAL ABSORPTION*					RED EMISSION EDGE			VIOLET EMISSION EDGE			K OF Ca	MEAN He	MEAN Fe
		H β	H γ	H δ	H ϵ	H ζ	H β	H γ	H δ	H β	H γ	H δ			
1927															
July 29.780	112.276	-17	-16	-21	-6	-47	174	152	153	-219	-209	-182	-32	-21	-21
Aug. 1.803	115.299	-18	-17	-18	-9	-53	174	173	144	245	189	218	+5	-5	-12
10.798	124.294	-12	-11	-9	-5	-31	182	143	155	218	176	172	-4	-28	-16
11.802	125.298	-8	-10	-7	-0	-24	188	164	154	208	161	196	+4	+3	+7
14.847	1.717	-7	-2	+1	+9	...	211	173	...	187	168	...	+3	-3	-4
21.797	8.667	+4	+6	+11	+16	-4	197	180	167	206	188	149	+5	+19	+8
25.816	12.686	+7	+13	+15	+22	+6	181	179	172	199	188	160	+14	+22	+2
Sept. 1.728	19.598	+33	+37	+35	+38	+49	203	184	...	215	201	...	+34	+60	-12
2.753	20.623	+31	+29	+29	+44	+24	212	165	149	200	192	132	+43	+54	-13
5.770	23.640	+26	+26	+30	+35	+6	178	196	191	203	181	173	-6	+30	+8
1928															
15.782	33.652	+30	+26	+21	+29	-5	206	195	191	212	191	165	...	+45	+13
18.775	36.645	+27	+30	+26	...	...	196	182	182	206	202	161	...	-19	-10
19.792	37.662	+33	+30	+17	+35	-40	197	195	183	193	188	160	-62	+33	+4
20.758	38.628	+36	+23	+21	...	...	179	210	...	190	193	...	...	+48	-3
Oct. 2.785	50.655	-11	+2	+1	...	...	184	179	...	213	174	...	...	+34	-11
3.716	51.586	+2	-9	-14	...	...	165	176	...	187	177	...	...	-12	-12
4.792	52.662	+5	+9	+4	0	...	183	177	214	195	159	175	+7	+13	-9
8.712	56.582	+4	+8	+5	+11	-18	189	180	161	208	174	146	+3	+1	+10
9.715	57.585	+6	+7	+5	+11	-25	195	154	162	226	179	176	-2	+1	-12
10.708	58.578	0	+6	+10	+14	-16	183	167	152	212	184	147	+2	+6	-14
1929															
16.717	64.587	-7	-1	+5	+9	-26	157	121	130	222	186	141	+4	+4	-7
18.679	66.549	-1	0	+1	+8	...	149	150	...	206	190	...	...	+5	-2
23.763	71.033	-20	-6	-2	+4	-30	186	121	112	222	178	143	-2	+3	-14
25.732	73.002	-8	-7	-9	-1	-35	162	139	128	202	212	174	-9	-8	-12
30.715	78.585	-13	-10	-9	+3	...	158	136	131	192	145	162	...	+1	-10
Nov. 6.702	85.572	-19	-14	-13	-11	-45	188	152	144	217	216	211	-4	+19	-16
12.705	91.575	-24	-16	-19	-3	-54	177	162	176	227	219	186	-1	+11	-17
18.627	97.497	-18	-34	-34	-19	...	181	173	169	227	222	201	-6	...	-38
Dec. 3.640	112.510	-9	-19	-18	-13	-49	184	139	164	230	185	174	+10	-13	-13
21.613	3.857	+1	+7	+4	+17	+8	197	164	155	189	182	134	+11	+15	+3
1928															
Jan. 28.513	41.757	+17	+11	+11	+8	-32	210	178	180	219	174	206	-11	+4	-7
Feb. 1.562	45.806	+1	-4	-9	-31	-25	197	166	178	-195	-186	-196	-6	-6	+6

* The values for $H\beta$, $H\gamma$, and $H\delta$ are weighted means of measures on the central absorption edges and their bisection. This procedure was used because the average of the settings on the edges agreed very well with the settings on the absorption center.

The variations of the relative intensities of the hydrogen emission components shown in Figure 2 for the single-prism spectrograms appear to be in substantial agreement with those of the two-prism plates.

The variations in intensity of the central absorption of $H\gamma$ and $H\delta$ relative to the continuous spectrum at these lines are shown by the curves at the top of Figure 2. The variation is similar for the two

lines. The absorption is a maximum relative to the continuous spectrum at a phase of approximately 18 days. This precedes the phase of maximum positive velocity, shown later in this paper, by about 10 days and confirms the results of Lockyer. The absorption is a minimum at a phase of approximately 90 days. The secondary variation is marked, with a minimum at phase 45 days and a maximum at phase 56 days.

Radial velocities and widths of hydrogen emission.—The radial velocities are given in Table I. The velocity-curves for the hydrogen

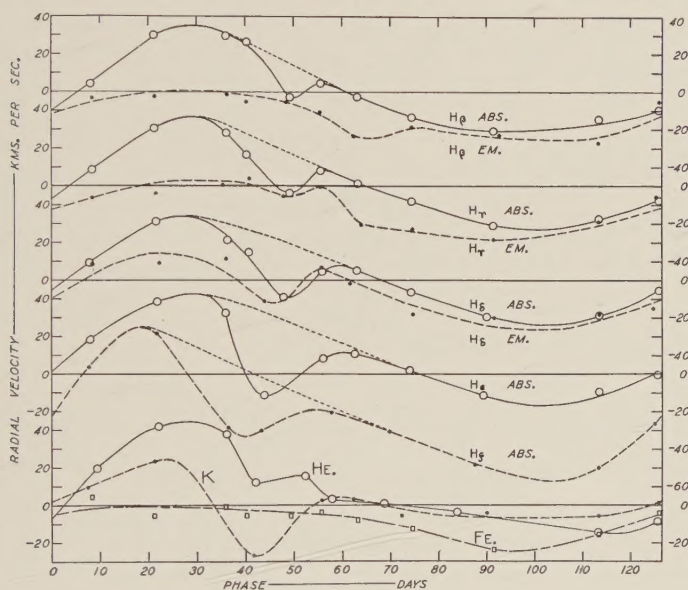


FIG. 3.—Radial velocity of spectral lines of ϕ Persei

absorption lines, based upon weighted mean places, are given in Figure 3. The curves have, in general, the same form but differ in some respects. A striking difference is the secondary variation, which occurs on the descending branch after maximum positive velocity. It becomes progressively more pronounced with decreasing wave-length. It appears earlier, increases in magnitude, and persists longer for lines of shorter wave-length, which is a strong confirmation of the results noted for the secondary variation of the relative intensities of the hydrogen emission components. These pro-

gressive variations are shown in Figure 4 by curves representing the isolated secondary velocity. They suggest that this variation is caused by a disturbance which affects the lower atmospheric levels of the star more than the higher levels, assuming that the lines of shorter wave-length originate at lower effective levels.

In isolating the secondary variation from the main velocity-curve, smooth curves were drawn in such a manner that the secondary variations were entirely below these curves. This procedure is suggested by the natural trend of the curves and is justified since the smooth

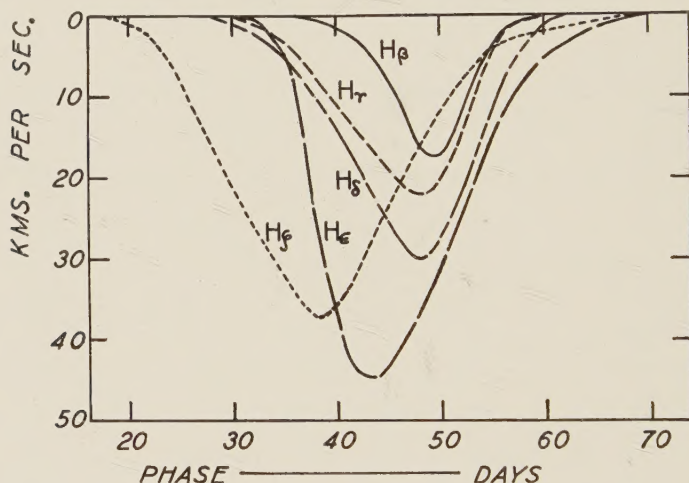


FIG. 4.—Isolated secondary velocity of the hydrogen absorption lines of ϕ Persei

curves thus formed are essentially the same for $H\beta$, $H\gamma$, $H\delta$, and also for $H\epsilon$, provided a constant correction of -8 kilometers is first applied to this curve. It should be added that the measures of $H\epsilon$ are rendered uncertain by the proximity of the H line of $Ca II$. The curve for $H\zeta$ is doubtless influenced by blending with the line $\lambda 3888.65$ of $He I$. Since both the hydrogen and the helium absorptions vary in intensity, the position of the resulting blend is rendered uncertain. The main variation is undoubtedly produced by the same cause. Similar velocity-curves should therefore be expected for the different hydrogen lines. Since such curves are obtained by isolating the secondary velocity variation in this manner, the method appears to be a rational one.

The secondary velocity variation, interpreted as radial motion in the line of sight, indicates a mass of hydrogen gas which begins to have an apparent motion of approach toward the observer immediately after maximum positive velocity (recession) of the main variation. This apparent motion of approach reaches a maximum value and then decreases again to zero at the phase where the main positive velocity has decreased approximately to zero. It should be noted

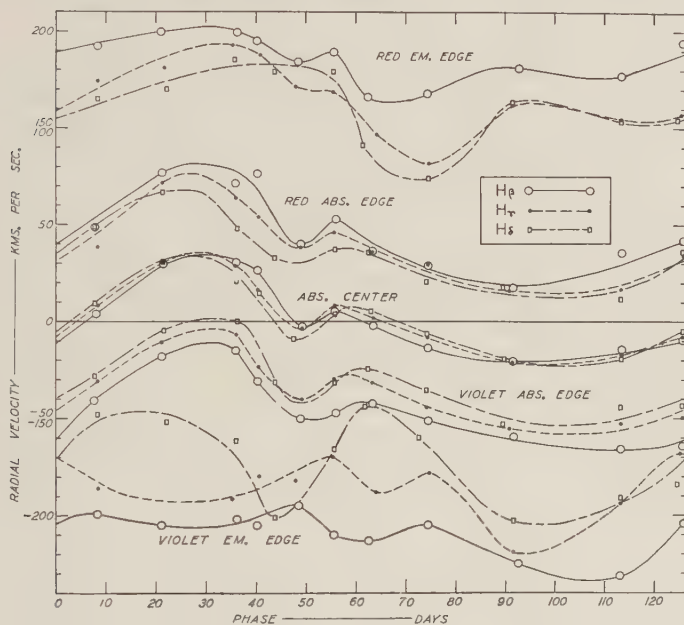


FIG. 5.—Radial velocity of hydrogen emission and absorption edges of φ Persei

that this interpretation of the secondary variation does not require a subsequent recession of this mass of gas relative to the observer.

The velocity-curves for K of calcium, for the mean of the helium lines, and for the mean of the ionized iron lines are given at the bottom of Figure 3. The K line exhibits the maximum positive velocity and the secondary variation. For the remainder of the period the velocity is practically constant. The line appears strong between phases 0 and 16 days. At the maximum and during the secondary variation it appears weak. This and the fact that it shows little variation in

velocity during the greater portion of the star's period, suggest that its origin is chiefly interstellar.

The mean velocity-curve for the helium lines is similar to the velocity-curves for the hydrogen absorption lines. The helium lines differ from the hydrogen lines with respect to intensity, being strong between phases 50 and 86 days and weak during the remainder of the period. A secondary velocity variation is indicated near phase 50 days.

TABLE II
MEAN WIDTHS OF HYDROGEN EMISSION LINES AND
COMPONENTS OF φ PERSEI IN ANGSTROMS

PHASE (DAYS)	TOTAL EMISSION			RED COMPONENT			VIOLET COMPONENT		
	H β	H γ	H δ	H β	H γ	H δ	H β	H γ	H δ
8.403.....	6.32	5.22	4.28	2.32	1.82	1.58	2.56	2.24	1.64
21.284.....	6.55	5.42	.....	1.96	1.60	.....	3.05	2.62	.....
22.132.....	.....	.....	4.42	.....	.....	1.47	.....	.....	2.03
35.986.....	6.54	5.58	4.76	2.08	1.84	1.87	3.05	2.71	2.20
40.192.....	6.47	5.48	.....	1.91	2.02	.....	2.82	2.35	.....
43.782.....	.....	.....	5.21	.....	.....	2.00	.....	.....	2.33
49.349.....	6.16	5.12	.....	2.29	1.99	.....	2.39	2.01	.....
55.010.....	6.46	4.94	4.72	2.19	1.81	1.94	2.61	2.04	1.83
61.582.....	.....	.....	3.90	.....	.....	1.42	.....	.....	1.68
63.238.....	6.10	4.83	.....	2.05	1.60	.....	2.76	2.25	.....
74.607.....	6.06	4.51	3.88	2.29	1.48	1.39	2.49	1.92	1.68
91.548.....	6.57	5.53	5.01	2.67	2.15	2.01	2.66	2.35	1.98
113.362.....	6.61	5.07	4.72	2.28	2.01	1.95	2.68	2.05	1.99
124.796.....	.....	.....	4.64	.....	.....	1.70	.....	.....	1.94
125.978.....	6.44	4.77	.....	2.45	1.82	.....	2.26	1.72	.....

The mean curve for the ionized iron lines shows only a negative velocity with respect to the center of mass velocity. The velocity is zero at phase 28 days when the velocity of the hydrogen lines is a maximum. The minimum is similar to that for the hydrogen lines, occurring at phase 96 days with a minimum velocity of -24 km/sec.

The displacements of the emission and absorption edges of the hydrogen lines expressed as radial velocity are shown by the curves in Figure 5. The velocity-curves for the central absorption of hydrogen are also plotted for comparison. The widths of the total emissions, of the emission components, and of the central absorptions

are related to the distances between the respective velocity-curves. The widths in angstroms for the emission lines and components are given in Table II, and the changes are shown by the curves in Figure 6.

The velocity-curves for the red emission edges of $H\beta$, $H\gamma$, and $H\delta$ are similar in form during the last half of the period but differ in the first half. The secondary variation is pronounced in $H\beta$, is only indicated in $H\gamma$, and is absent in $H\delta$, thus showing the same pro-

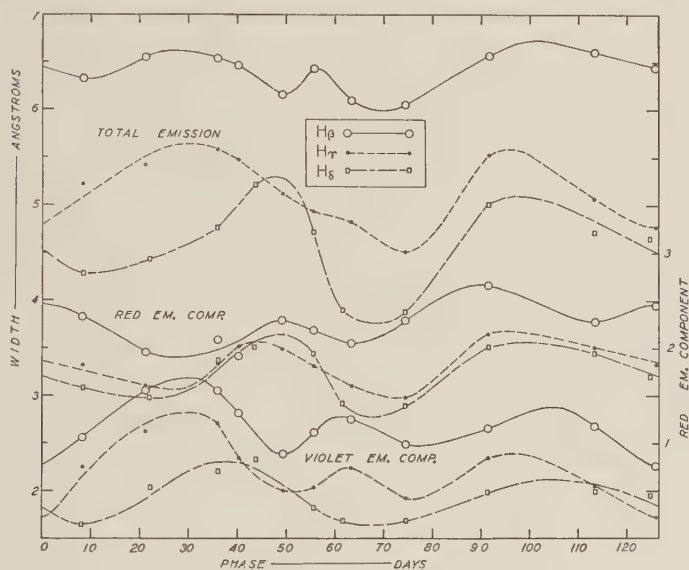


FIG. 6.—Widths of the hydrogen emission lines and components of φ Persei

gressive change found in the relative intensity of the emission components and in the total emission width. The maximum displacement to the red occurs at a later phase than for the absorption. This lag in phase increases for lines of shorter wave-length, a fact also to be noted in the widths of the total emission. The maximum displacement toward the violet, between 70 and 80 days, corresponds to the phase at which the total width of the emission lines is a minimum, and at which the intensity of the red emission component is a maximum relative to the intensity of the violet emission component. Between 90 and 100 days the red emission edges show a displace-

ment toward the red, while the hydrogen absorption lines show a displacement toward the violet. At this phase the widths of the red emission components are a maximum.

The velocity-curves for the violet emission edges of $H\beta$ and $H\gamma$ are similar in form, and during the last half of the period show variations similar to the hydrogen absorption, namely, a displacement toward the violet. During the first half of the period, however, when the hydrogen absorption lines show a displacement toward the red, the violet emission edges of $H\beta$ and $H\gamma$ show a displacement toward the violet. They show a similar secondary variation, but at a later phase than the hydrogen absorption.

The velocity-curve for the violet emission edge of $H\delta$ is different. It resembles the curves for hydrogen absorption at phases of maximum and minimum velocity. The secondary variation between phases 40 and 70 days is exceedingly great. The secondary minimum at 44 days corresponds to the phase of maximum emission width of $H\delta$, while the secondary maximum at 64 days corresponds to the phase of minimum emission width.

The widths of the hydrogen emission (Fig. 6) are greater for lines of longer wave-length. This fact was noted by Curtiss for Be stars¹¹ and was later verified by Dustheimer for φ Persei. The range of variation in width is greater for lines of shorter wave-length. The curves show two maxima and two minima in the period of 126.6 days, which was also found by Dustheimer from his measures of the one-prism spectrograms. The phase of the first maximum is greater, and of the second maximum is smaller, for lines of shorter wave-length. The phases of the two minima are the same for $H\beta$ and $H\delta$, while for $H\gamma$ the first minimum occurs at an earlier phase and the second minimum occurs at a later phase. The secondary variation is pronounced in $H\beta$, is doubtfully indicated in $H\gamma$, and appears to be absent in $H\delta$. This progressive change of the secondary variation with wave-length confirms the two-prism microphotometric results discussed earlier in this paper (see Fig. 2).

The curves for the widths of the violet emission component of $H\beta$, $H\gamma$, and $H\delta$ are similar in many respects to the curves for the total emission widths. The progressive changes in the phase at the first

¹¹ *Pub. Obs. U. of Michigan*, 3, 1, 1923.

maximum and in the secondary variation are practically identical with those noted for total widths.

The curves for the widths of the red emission component of $H\beta$, $H\gamma$, and $H\delta$ show in many respects variations just opposite to those observed for the widths of the violet emission components. This is particularly true for $H\beta$. It is apparent, therefore, why the microphotometric results for $H\beta$ show such great changes in the relative intensities of the two emission components. On the other hand, the curves for the widths of the violet and red emission components of $H\delta$ show practically the same variations. These similar variations in the width of the emission components of $H\delta$ explain why the microphotometric results for this line show comparatively small variations in the relative intensity.

At phase 90 days, when the violet emission edges show a violet displacement similar to that of the hydrogen absorption lines, the red emission edges show a red displacement; and at phase 30 days, when the red emission edges show a red displacement similar to that of the hydrogen absorption lines, the violet emission edges show a violet displacement. At these phases the widths of the total emission lines are maxima. It may be said, therefore, that an emission velocity-curve for this star, formed by taking the average of the settings on the outer emission edges, has little meaning. Such a curve can be interpreted readily only when the two edges show identical variations. The values obtained by taking the average of the settings on the outer emission edges are plotted in Figure 3 as broken curves. As expected, the range of the "apparent" emission velocity is small. The emission velocity is roughly zero at the phase where the absorption velocity is a maximum. The minimum occurs at the same phase as the minimum of the absorption and is approximately of the same magnitude. This behavior may be interpreted on the assumption that when the absorption velocity is a maximum, at phase 30 days, the central absorption is greatly displaced toward the red relative to the emission, thus exhibiting a maximum width for the violet emission component, a minimum width for the red emission component, and a maximum intensity of the violet emission component relative to the red emission component. When the absorption velocity is a minimum, at a phase of about 90 days, the emission

velocity is also a minimum and nearly of the same magnitude, thus indicating approximately equal widths for the two emission components, even though the width of the red emission component is then at its maximum. However, at this phase the intensity of the red emission component is greater than the intensity of the violet emission component, instead of being equal to it. Furthermore, the intensity of the red emission component is a maximum relative to the intensity of the violet emission component at an earlier phase, 75 days, corresponding to the phase when the width of the emission is a minimum and when the width of the violet emission component is greater than the width of the red component. It is apparent, therefore, that the intrinsic intensity distribution of the emission lines must vary greatly during the star's period, in addition to variations caused by the relative displacement of the absorption with respect to the emission.

It should be added that the foregoing spectral variations of φ Persei occur without conspicuous variations in the visual brightness of the star.

DISCUSSION

Any system which is proposed for φ Persei must account for the foregoing spectral variations. Simple orbital motion, as suggested by previous investigators, is not capable of explaining the observed spectral variations. If it is assumed, however, that the two stars of a binary system contribute to the emission of hydrogen, then changes in the width and in the intensity of the hydrogen lines would be produced by the relative motions of the superimposed lines from the two stars. These changes may be enhanced somewhat by the photographic effects or shifts discussed by Frédette. Even such a modified binary system cannot account adequately for all of the observed spectral variations of φ Persei.

Curtiss¹² suggested radial pulsation for the spectrum variables of the φ Persei group. Dustheimer¹³ adopted the pulsation hypothesis for φ Persei and suggested a secondary pulsation of shorter period and smaller range to explain the secondary velocity variation. This hypothesis must assume that the inconspicuous light variation ob-

¹² *Pub. A.A.S.*, 34th Session, 1925; *Pub. Obs. U. of Michigan*, 4, 174, 1932.

¹³ *Pop. Astr.*, 35, 484, 1927; dissertation University of Michigan, unpublished.

served by Guthnick and Güssow is explained by periodic changes in the effective temperature of the photosphere. It does not account satisfactorily for the cyclic variations in the widths of the emission lines and components in one-half of the star's velocity period, since the range of velocity variation of the emission edges of hydrogen is of the same magnitude as the range of the central absorption (see Table III). The assumptions of a transparent atmosphere and no appreciable occultation by the photosphere are therefore not sufficient. The chief objection to the pulsation hypothesis is that it requires a change in the radius of the star which is greater than the radii of normal B-type stars.

TABLE III
RANGE OF VELOCITY VARIATION OF THE
HYDROGEN LINES OF φ PERSEI

	$H\beta$	$H\gamma$	$H\delta$
	km/sec	km/sec	km/sec
Red emission edge. . .	34	61	61
Central absorption. . .	51	52	50
Violet emission edge. .	36	51	57

The writer suggested, at the time this work was completed in 1928,¹⁴ a star of very low density, pear-shaped or apoidal in form, with a very extensive atmosphere and a small and ill-defined photosphere, and which is rotating about a line greatly displaced from the effective center of the apparent photospheric area with a period of 126.6 days. It was assumed, further, that the star's atmosphere is pulsating in the same period, that it is contracting while the apparent photosphere is receding, and that it is expanding while the apparent photosphere is approaching; while a secondary pulsation was assumed for the secondary variation. Finally, it was assumed that the hydrogen absorption originates in the atmosphere between the photosphere and the observer, while the hydrogen emission originates in the atmosphere projecting beyond the photosphere at right angles to the line of sight, as suggested by Rosseland.¹⁵ The amplitude of pulsation required in this hypothesis would be much smaller than is required by pulsation alone. The arguments ad-

¹⁴ *Iowa Acad. of Sci. Proc.*, **36**, 281-93, 1929.

¹⁵ *Ap. J.*, **63**, 218, 1926.

vanced in favor of the pulsation hypothesis apply equally well; and the effects of rotation, pulsation, and the shape of the star are such as to explain the observed variations of φ Persei more satisfactorily.

The most promising hypothesis for explaining the spectral variations of φ Persei consists in assuming a system of orbital motion in which each star is rotating rapidly about its axis, combined with an apparent atmospheric pulsation of expansion in the companion star at the phase of the secondary variation. Certainly the truly periodic variations of φ Persei with respect to width and intensity of the hydrogen emission and with respect to radial velocity of the hydrogen absorption can be explained satisfactorily by this system. It is only necessary to assume that both of the rotating stars of the binary system have very extensive atmospheres which contribute to the hydrogen emission, the emission originating in the atmospheres of the stars at right angle to the line of sight, and that the hydrogen absorption originates mainly in the outer atmosphere between the observer and the fairly well-defined bright photosphere of the primary star. The great widths of the hydrogen emission lines and the variation in one-half of the star's velocity period are explained readily by the resultant motion produced by rotation and orbital motion in the line of sight. For example, at maximum positive velocity (phase 30 days) the primary star is receding in orbital motion. The red emission component of hydrogen is greatly displaced to the red, owing to rotation, since it originates in the receding atmosphere of the primary star, which itself is receding because of orbital motion. The violet emission component of hydrogen is displaced toward the violet, owing to rotation, since it originates in the approaching atmosphere of the companion star, which itself is approaching because of orbital motion. Since the central absorption of hydrogen is produced mainly in the atmosphere of the receding primary star, it appears to be displaced toward the red with respect to the violet emission component. The violet emission component should therefore show maximum width and greatest intensity relative to the red emission component at this phase. Furthermore, the width of the total emission should be a maximum because of opposite displacements of the two emission edges. It should be noted that these observations are in com-

plete agreement with the results presented in this paper. Obviously, the reverse occurs at the phase of maximum negative velocity; and it is to be noted that at this phase the red emission component shows maximum width and approximately maximum intensity relative to the violet emission component. The width of the total emission shows a maximum for the same reason as at maximum positive velocity. At the intermediate phases of zero velocity for the absorption of hydrogen the widths of the emission components should be minima and the relative intensities of the two emission components should be equal. Also, the widths of the total emission should be minima. Thus, the main and truly periodic variations of φ Persei can be explained satisfactorily by this binary system.

McLaughlin¹⁶ recently suggested a rotating and pulsating mechanism for Be stars. Dodson¹⁷ has successfully applied this hypothesis to explain the irregular cyclic spectral variations of γ Orionis. There seems to be no reason why a pulsation of this nature could not be operative in a rotating star of a binary system, such as β Lyrae, for example. The spectral variations produced by this type of pulsation could be quite independent from the truly periodic spectral variations caused by orbital motion and axial rotation, and could be merely superimposed upon them. The pronounced secondary variations of φ Persei, which vary progressively with wave-length and probably vary also with time, would appear to be explained by atmospheric pulsation of this type.

It should be noted, however, that immediately after maximum positive velocity resulting from the orbital system suggested above, the primary star, with the well-defined and bright photosphere, may be partially eclipsed by the extensive, rarefied, and transparent atmosphere of the companion star. It is noteworthy that this is the phase at which the pronounced secondary variations occur in φ Persei. This condition of partial eclipse could produce spectral variations which may be termed "secondary variations" and which would probably vary progressively with wave-length. At this phase an apparent atmospheric pulsation of expansion or approach along the

¹⁶ *Proc. Nat. Acad.*, **19**, 44, 1933.

¹⁷ Dissertation, University of Michigan, 1934, *Ap. J.*, **84**, 180, 1936; abstract in *Pub. A.A.S.*, **8**, 109, 1935.

line of sight may be produced in the intervening extensive, rarefied, and transparent atmosphere of the companion star, owing to excitation by radiation from the hot photosphere of the partially eclipsed primary star. Obviously, secondary variations would result also in the relative intensity of hydrogen absorption and emission. This type of excitation would necessarily be continuous, but its effect would be observed only during the partial eclipse. It is probable, however, that, owing to rotation, the excitation would be very much more effective in the receding atmosphere of the companion star at the beginning of the partial eclipse than in the approaching atmosphere of this star toward the end of the eclipse, which is in agreement with the fact that the observed secondary velocity variation of hydrogen absorption appears and practically subsides before the absorption velocity has decreased to zero. This interpretation of the secondary variations of φ Persei appears to be the most promising of any so far suggested.

It is with great pleasure that the writer expresses his thanks to the late Professor Ralph H. Curtiss for making the investigation possible and for his kindly criticism, suggestions, and direction; and to those who have helped in procuring the spectrograms.

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